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The Effect Of TiN Coatings on the Rolling Contact Fatigue Behavior of M50 Bearing Steel

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There is a continuing requirement for improved bearing performance for both commercial and military applications. Service temperatures are increasing steadily due to increased power requirements and corrosion of components remains a major concern as well, particularly for bearings in military systems. In our ongoing study, a number of different coatings were applied to VIM-VAR M50 bearing steel to improve both corrosion resistance and rolling contact fatigue behavior. This report deals specifically with coatings produced by the ion beam assisted deposition [IBAD] of TiN, details of the coating process, and test results obtained. The rolling contact fatigue performance of IBAD TiN coated M50 samples demonstrated increased lifetime performance and durability for a 1 um thick coating. Preliminary data on corrosion properties is also presented.

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INTRODUCTION

The quest to improve tribological performance of drive train components in helicopters and other Army mechanical moving assemblies is a critical and compelling one. The effort to improve useful lifetimes for these components is propelled by two driving forces :

1] the requirement for drive train components to withstand the higher loads, speeds, and temperatures demanded in emerging and advanced Army systems, and

2] the reduction of surface degradation of presently fielded components from environmental effects, e.g., surface corrosion from moisture contaminated lubricants. An estimated 95% of replacements for rolling element bearings result from surface distress.

It was toward these ends that the U.S. Army Materials Technology Laboratory [MTL] established a program to improve lifetime performance of bearing / gear materials and to seek additional performance improvement of these materials through the utilization of surface modification and/or coatings to promote surface damage resistance. The emphasis of this program is implementation and insertion of improved performance materials in critical components of Army weapons systems. That is, the project serves as a vehicle for down-selection of promising materials and processes for further full-scale component and system testing. Accordingly, attempts have been made to standardize testing and characterization techniques wherever possible.

With the support of U.S. Army AATD/AVSCOM# a cooperative program with the Naval Research Laboratory was established to process and characterize low energy ion beam assisted deposition [IBAD] of TiN. For background on this effort consult Reference 1. This present paper will report on rolling contact fatigue results and corrosion studies performed on M50 steel coated with IBAD TiN. Vacuum induction melted-vacuum arc remelted [VIM-VAR] M50 substrates were selected because M50 is the current standard aircraft turbine engine bearing material and the MTL program is targeted toward both currently fielded systems as well as emerging and advanced systems.

Aviation Applied Technology Directorate/ Aviation Systems Command

Appendix A, 'Comments on Goals and Objectives", contains the background, emphasis and justification for conducting this project as well as its advantages to the U.S. Army.

MATERIALS AND EXPERIMENTAL PROCEDURES

Ion Beam Assisted Deposition Process

The concept of ion beam assisted deposition is a relatively simple one and the process an attractive means for coating surfaces. This technique of evaporating or sputtering atoms from one material for surface deposition on a substrate, while simultaneously implanting the substrate/deposition coating with ions, has some distinct advantages. The thickness of the resultant coating can be much greater than the depth of penetration occurring with conventional ion implantation. Indeed, to achieve any great depth of ion penetration [0.1 to 0.4 μm], one must utilize high energy ion implantation of the order of 100 keV. High dosage rates can be employed to increase concentration and affect wear but this poses a potential problem with thermal tempering of the steel substrate and subsequent degradation of rolling contact fatigue properties. The primary advantage of ion implantation is a modified microstructure it imparts to the substrate surface layer, resulting in no discernable bond line or related adhesion problems often attendant with conventional [PVD-CVD] coating or plating. The same benefit as ion implantation, a modified substrate surface layer, is realized with the IBAD process as a consequence of coating and substrate atom intermixing at the interface. Furthermore, this can be accomplished at significantly lower heat loads than those that accompany ion implantation, due to the lower ion energies employed with IBAD. Additional advantages include a wide range of producible coating thicknesses, without thermal degradation of the substrate. Establishment of an effective IBAD coating is governed by the ability to build up an equiaxed or textured [but non-columnar] grain structure in the coating thickness. With close control of the coating parameters in the IBAD process[1] this has been achieved. Columnar grain growth in coatings contribute to decreased corrosion resistance, susceptibility to stress corrosion cracking, and poor adhesion properties under heavy loads.

Previous studies at NRL[2] indicated that low energy IBAD coatings [1 keV] could be as effective as standard [30 keV] IBAD processing. The resultant lower heat loads, coupled with the ability to closely control ion-to-atom arrival ratios at low energy, provided the impetus to evaluate this coating technique in the rolling contact fatigue/bearing program. Accordingly, ten specimens, representing four different processing parameters [Table 1], were prepared at NRL for rolling contact fatigue [RCF] testing.

IBAD processing involved reactive deposition of TiN at room temperature with concurrent ion bombardment. Specifically, Ti vapor, obtained by electron beam evaporation, was reacted at the coating surface with molecular nitrogen in a high vacuum system that was backfilled with a low pressure atmosphere of nitrogen gas. During deposition, the growth surface was simultaneously irradiated with an ion beam consisting of either 30 keV $N^+{}_2$, 1 keV $N^+{}_2$ or 0.5 keV Ar^+ ions. The circumference of both ends of each rod was coated along a one inch length of the rod. This was accomplished by rotating the rod about its long axis at the intersection of the vapor stream [incident from below] and the ion beam [from the side], as shown in Figure 1. The axis of rotation, at right angles to both fluxes, was positioned 30 cm above the evaporator. The 30 keV ion beam was supplied by a mass analyzed, medium current Varion/Extrion ion implanter and the lower energy ion beams were obtained from a Kaufman style ion gun of the type commonly used for sputtering.

In some cases, the region of the rod to be treated was limited by apertures placed in the paths of both the ion beam and the Ti vapor source. The apertures were adjusted to limit the angle of incidence to less than 45 degrees from the surface normal. This eliminated the higher sputtering rates that would have resulted from low ion beam glancing angles of incidence with the specimen. Apertures were used when sputtering effects were greatest [with 30 keV ions] and generally not used for bombardment with 0.5 keV ions since, under these circumstances, sputtering was relatively insignificant. During each deposition, only half of each rod was exposed at a time, while the other half was inserted in, and covered by, a sample holder at the end of a rotating, water cooled, vacuum feed through.

Since the ion and vapor fluxes are at right angles to one another, vapor deposition and bombardment at each point on the film was generally sequential. However, the rod rotation [30 rpm], together with the modest deposition rate [0.1 nm/s], meant that only one monolayer of film was deposited prior to exposure to ion bombardment. Consequently, bombardment was effectively simultaneous with deposition. A quartz crystal was used for monitoring film thickness and deposition rate. Additional control over the atmosphere surrounding the growing films was provided by an enshrouding anti-contamination cryogenic surface [cold wall] maintained at liquid nitrogen temperature.

A closed loop computer controlled feedback system was used to monitor and control the deposition parameters such that the ratio, R, of the ion flux to the vapor flux at the growth surface was held constant throughout each deposition. All samples were sputter cleaned immediately before film deposition. Films were grown and tested for the four different sets of processing parameters outlined in Table 1. This then, represented a range of processing conditions which we anticipated, upon testing and comparison, would establish the direction to proceed in producing a viable wear coating with the IBAD technique. Several previous studies of cutting tools coated with TiN[3-6], or ion implanted[7], indicated improved lifetime for cutting operations and it appeared worthwhile to determine if an analogous effect would occur with rolling contact behavior. As a baseline for comparison, uncoated M50 steel rods from the same heat as the coated ones were tested and evaluated. The M50 steel used in this phase of the investigation was supplied by NRL from a heat of material used as a substrate for other extensive RCF tests of various species [Cr, Ti, Ta, N_2], implanted at different energies and dosage rates. Those tests were carried out by the Naval Air Propulsion Center [NAPC][8] at 700 ksi Hertzian, 12,500 rpm, under elastohydrodynamic [EHD] lubrication conditions. For this set of RCF conditions, lifetime performance was not significantly improved by ion implantation .

Rolling Contact Fatigue Testing

All rolling contact fatigue testing for the present effort was performed on a ball/rod rig [developed by Federal-Mogul[9] and now produced by NTN], under the following conditions ·

Hertzian Stress = 786,000 psi, [5.42 GPa]
Rotational Speed = 3600 rpm
Lubrication supply = 8-10 drops per minute
Lubrication type = MIL-L-23699
Specimen length = 3.0 in., +0.100"/ -0.000"
Specimen diameter = 0.375 in., +0.0000"/ -0.0002"
M50 Surface finish = 2-4 μ in. AA
Temperature = 20-25 ^{o}C

The rolling contact fatigue rig is shown in Figure 2 and four stations were operated simultaneously to speed up acquisition of data. Sixteen to twenty wear tracks and associated fatigue spalls were obtained for each specimen condition [coating process parameter] and the specimens were alternated among the test stations to minimize any systematic experimental error.

RESULTS

RCF Tests of Coatings

The results, from coated and uncoated specimens, plotted as Weibull Distributions, ie., accumulated failure vs. stress cycles, are shown in Figure 3. Additionally, Table 2 shows the calculated B10 and B 50 [10% and 50% accumulated failure] for the different specimen conditions.

Comparison of the Weibull Distribution plots and the calculated values in Table 2 reveal that the 0.25 μm thick coated samples do not display any appreciable performance improvement. Our criteria for claiming significant lifetime improvement is a minimum two-fold increase in B50 life. The results were somewhat unexpected, considering the improved wear lifetimes of tools in prior studies, and previous RCF studies of TiN coatings on other substrates[10,11] and on M50[12]. Testing in [11] was performed on a twin-disc [gear type] material tester under rolling conditions. Perhaps the effective contact area of the discs, which is different from that of the ball/rod rig, account for their best results with 0.25 μm coatings but poor results from similar thickness coatings in our studies. Testing at MTL of different coatings on M50 steel, including ion plated ZrN and electroplated thin dense chromium, all 1.0 μm in thickness[13], showed improvement over the base material meeting the specified criteria. A decision was made to IBAD coat the M50 substrate rods to a thickness of 1.0 µm, on a limited basis, and test to determine if a thickness dependence for improved RCF results existed with these coatings.

The Naval Research Laboratory coated two additional M50 rods with IBAD TiN to a nominal thickness of 1 µm. The M50 substrate material used was from a different heat than that utilized in the earlier experiments. To ensure unambiguous results for comparison purposes, uncoated samples of this material were RCF tested as well. The coatings [on the cylindrical surface of both ends of each test specimen] were produced under the following conditions:

Samples were rotated at 6 rpm and coatings were deposited in a background vacuum of 10^{-5} Torr N_2. Bombardment took place with 0.2-0.5 keV Ar^+ ions and the substrate was water cooled during treatment. Table 3 shows the other relevant parameters for the four ends of the two specimens:

Five wear tracks were run on each end of the coated specimens. Normally, 16 to 20 RCF tracks are obtained to provide the statistical confidence that we desire. However, this was preliminary testing for comparison with our previous data. Of the four specimen ends tested, three produced several ball failures [ball spalls] and only one set resulted in all five rod failures, which were enough data points to plot a Weibull distribution. This set, 0.5 keV, R=0.3 of sample SR2, is shown plotted in Figure 4, along with the uncoated material, and the calculated B10 and B50 lifetimes are shown in Table 4.

The first feature to note with this data is that the uncoated specimens display a greater performance lifetime than the uncoated specimens from the prior tests. This material also has a higher slope on the Weibull plot, indicating less dispersion of the data points. Both substrates are M50 VIM-VAR steel with equivalent microstructure, hardness, carbide size, and presumably mechanical properties, but the steel tested originally [and subsequently coated with 0.25 µm TiN] was from a heat produced in the 1970's, while the improved values come from a more recent heat. The improvement shown for the uncoated samples may be the result of more closely controlled processing and perhaps better heat treat control. In any case, the comparison of interest is between coated and uncoated specimens to determine the effect of the coating compared to the uncoated substrate used, and Table 4 clearly shows the lifetime improvement achieved with a 1 μm thick TiN coating compared to the baseline. This does show indeed, that a thickness dependence exists for RCF improvement of coated samples, at least for this particular coating. It is worthwhile to note that the other 1 μm specimens tested may have even greater lifetime performance, based on the fact that the balls failed instead of the rods. Testing is continuing with a larger number of 1 μm coated specimens, and results will be published when available.

Corrosion Tests

As stated earlier, corrosion contribution to bearing failure is a significant factor, and corrosion resistance may be as important as tribological properties, [it is surmised, but not proven, that corrosion pits may be initiating sites for fatigue failure]. Accordingly, corrosion tests were performed at NRL to evaluate the resistance of the IBAD TiN coatings to crevice corrosion in a dilute NaCl solution. Pairs of one half inch diameter rods of M50 were coated with TiN, one of each pair on the cylindrical surface and one on the flat surface. Each pair was inserted in a teflon holder with the coated flat surface against the coated cylindrical surface, see Figure 5. Using ASTM D665 synthetic seawater, 3 ppm by weight of chlorides was added to MIL-L-23699B lubricating oil. Water content of the oil was then adjusted to 650 ppm by the addition of distilled water. The test specimens were immersed in the doped lubricant at room temperature for one hour. Following this, they were placed into test cells where they were suspended above 300 ml of distilled water. The cells were subjected to temperature cycling, holding at a temperature of 3 ^{o}C for 16 hours and then 65 ^{o}C for 8 hours, during a total time span of two weeks in order to simulate conditions of an engine operated intermittently. This is a standard test to evaluate crevice corrosion of bearing steels in aircraft that might be subjected to a marine environment where lubricating oil may become contaminated. Subsequent to corrosion testing, the samples were cleaned in an organic solvent and examined with an optical microscope. For the untreated M50 steel, considerable general and pitting corrosion was evident. By comparison, the surface of all the IBAD TiN coated samples were relatively free of either type of corrosion. Some pinholes did exist in the coating however, which could prove to be detrimental to long term corrosion resistance. Corrosion tests on the thicker coating [1.0 μm] are yet to be performed. Nevertheless, it is anticipated that the 1 μm coating will demonstrate greater corrosion resistance due to the fact that corrosion depends on film thickness, especially when it arises from pores. Ensinger et. al.[14] evaluated the corrosion potential of TiN films produced by four different techniques; arc evaporation [ARC], magnetron sputtering [MAG], activated reactive ion plating [ARIP], and IBAD. Corrosion protection potential of the coatings in a slightly acidic aqueous environment was determined for each process by recording current/potential plots. Their findings showed that the IBAD film performed best overall with the lowest recorded current, indicating a low corrosion rate. However, at longer potential cycles [greater than 400], ARIP TiN began to display a better corrosion resistance. The thickness of the ARIP film was 8μm compared to an IBAD film of 3μm and this increased thickness accounts for the improved performance of ARIP at later cycles. It should be noted that the ARIP processing temperature tempered the steel substrate so that RCF properties will certainly be substandard. Conclusively then, of the processes studied, the IBAD TiN films demonstrate the most favorable combination of corrosion resistance and RCF behavior.

Characterization

SEM investigation of the wear tracks of the 0.25 and 1 μm coated samples was conducted. Figure 6 shows two typical fatigue spalls for these samples. Inspection of the wear tracks revealed that, for the 0.25 μm specimens, those deposited at 1 and 30 keV suffered greater coating wear [more coating loss] than those deposited at 0.5 keV. The inference is that Ar ion bombardment of the TiN coating produces a more wear resistant surface than N_2 bombardment. Even so, there was no discernible difference in their RCF performance, and indeed, no improvement over the uncoated material. The coating loss of the thinner coated samples probably occurred in a short enough time frame so that it could not provide any fatigue advantage. If the coating removal rate were consistent for both thick and thin coatings, then it appears obvious that the 1 μm coating provides adequate protection for a sufficient time period to dramatically increase performance by fourfold. Curiously, the 1 μm coated samples showed a great deal of wear variability at approximately the same statistical lifetimes. Figures 7 through 14 show comparative SEM micrographs for each coating condition, along with typical wear tracks obtained on the rods. At this time we cannot offer an explanation to account for the apparent difference in coating removal [Figures 12 and 13] between samples coated using the same coating parameters, i.e.., 0.5 keV and R=0.5. Each of these samples produced a number of ball spalls, SR1=4 and SR2=2, so that RCF rod data did not supply sufficient performance statistics to reconcile the discrepancy. Based on the overall improved performance of the thicker coating, testing is continuing with 1 μm coatings to establish optimum coating parameters and to resolve the enigma of coating wear variability.

An analysis of track width compared to time-to-failure was performed to determine if a direct correspondence existed between the wear effect and the onset of fatigue. The assumption was that greater wear should produce a wider track and that rolling contact fatigue might occur after considerable wear had taken place. Figure 15 and 16 are bar graph displays of track width associated with each of the tests to failure [either rod or ball] for the 0.25 and 1 μm coated specimens. No linear relationship appears to exist, one consequence of unit width measurement being orders of magnitude greater than coating thickness, but still, it was readily apparent that some of the longer running specimens had a narrower track width than specimens that failed sooner. These results were substantiated with profilometer measurements of the track depths and compared to track widths and time to failure, as shown in Figures 17 and 18. Table 5 shows the RCF data for all specimens whose tracks were measured for depth and width. The profilometer measurements also revealed that the track depth was considerably greater than the coating thickness in all cases. Yet, in all instances for the 1 μm coatings, some coating was still in evidence in the wear track. This was verified by visual observation and SEM EDAX examination. It is apparent that during deformation of the substrate and creation of a wear track from high Hertzian induced cyclical stresses the elastic response of the coating closely conforms to the substrate deformation. This observation demonstrates the excellent adherence of these IBAD coatings, one of the major elements of concern in coating practice.

DISCUSSION

Optimum coating thickness is yet to be determined although published data[15] indicates that coatings greater than 2 μm tend to fracture. In this case, however, care must be exercised in interpreting that data. The PVD process utilized to produce the 2.7μm thick TiN coating in this study, tempered the steel substrate, resulting in a surface hardness of 55.6 HRC, with subsequent degradation of RCF lifetimes[10]. Consequently, the softened substrate would undergo considerable plastic deformation at 786 ksi Hertzian stress loading. This in turn creates additional stress, affecting the compliance of the coating with the substrate which, in turn, initiates fracture and chipping of the coating. The IBAD coating process, by comparison, produced no tempering of the steel specimens and hardness was maintained at 60-62 HRC. Continuing studies on a range of IBAD coatings will determine the optimum thickness for optimum improved performance.

Bearing manufacturers have known for many years that surface finish can affect bearing life. AFBMA## publishes tables for bearing grades, and although these primarily specify roundness and testing methods of manufactured lots, surface finish specifications are included. In production practice, however, surface finish variation between [for example] grade 10 and 25 is generally about 0.5 μ in. For our testing we elected to use grade 5, 52100 balls, surface roughened to 3-4 μ in., to standardize with bearing manufacturer's testing [Federal-Mogul, NTN, Timken]. Increased surface roughness [carefully controlled] allows timely acquistion of test results of a large number of data points, an important consideration for comparison down-selection. Moreover, it has been determined[16] that in field service, main shaft rolling elements are roughened from 0.5 μ in. to a range of 1 to 2 μ in. in less than 18 hours of operation. Thus, it appears reasonable that laboratory testing with surface roughened balls correlates with extended field operation. Surface roughness, in service, takes place due to microspalling of non-metallic particles embedded in the surface layer of the rolling elements. These SiC and Al_2O_3 particles are a consequence of ball-finishing operations. This occurrence may well explain the improvement produced in lifetime performance by coatings much thinner than the induced depth of maximum Hertzian stress. The coatings serve to prevent or delay surface particle microspalls which, under cyclical loading, are proposed to coalesce via crack propagation and form the macrospalls which limit bearing durability. It is generally recognized that, with the advent of VIM-VAR steels, the failure initiation sites moved from sub-surface inclusions to surface proximity. Thus, the study of surface phenomena in wear and fatigue acquired a heightened significance. Even so, there

Anti Friction Bearing Manufacturers Association

existed no explanation of a mechanism to account for improved performance attributed to thin coatings or surface modification. We offer an interpretation [spalling retardation] which we feel is representative of the events taking place in rolling element bearings.

Details of loading on bearing life has been well documented for many years[17]. Simply put, higher loads reduce life and vice-versa. In the quest to down-select from the plethora of materials, coatings, surface modifications and processes, it did not appear reasonable to test wide ranges of loading, particularly when results are predictable. Therefore, we have standardized on 786 ksi Hertz stress, a common test loading with bearing manufacturers and within the aircraft industry.

CONCLUSIONS

1. It is postulated, from this work and previous studies by Law and Antony[16], that the mechanism for improving bearing life by relatively thin coatings results from the coating retardation of microspalls that initiate from surface layer particles embedded in the steel.
2. Limited RCF testing on 1 µm thick IBAD TiN coated M50 steel show a definite lifetime improvement of nearly fourfold at B50 life.
3. Testing of similar 0.25 µm coatings showed no performance improvement and observations of the wear [coating removal] rate indicate that material loss at this thickness takes place too quickly to affect fatigue life substantially.
4. Results indicate a thickness dependence of these coatings for rolling contact fatigue improvement.
5. Excellent adherence of the IBAD coatings under excessive stress loading has been established.
6. Corrosion tests of TiN coated M50 show that the IBAD coatings provide increased corrosion resistance.
7. Continuing studies of this system will determine the optimum coating parameters and optimum thickness.

ACKNOWLEDGMENTS

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An abbreviated version of this report [prescribed by space limitations] was presented at the Fifth International Conference on Surface Modification Technologies held in Birmingham, UK. Subsequently, this work was selected by the Institute of Metals, as one of only six papers from the conference, to be published in the IM journal Surface Engineering and appeared in Vol. 7, No. 4, pp 319-326. The presentation was also published in the Surface Modification Conference proceedings, Surface Modification Technologies V, ed. T.S. Sudarshan and J.F. Braza, The University Press, 1992.

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TABLE 1

Process Condition for TiN IBAD Coatings

keV	Ion to Atom Arrival Ratio	Coating Thickness
1	0.03	0.25 µm
30	0.03	0.25 µm
0.5	0.20	0.25 µm
0.5	0.40	0.25 µm

Table 2

Stress Cycles to Failure for 0.25 µm coatings

Condition	B 10	B 50
Uncoated	2,745,946	7,912,714
1 keV, R=0.03	4,099,406	7,902,961
30 keV, R=0.03	3,549,115	7,429,546
0.5 keV, R=0.20	2,973,800	8,469,120
0.5 keV, R=0.40	1,899,832	6,508,070

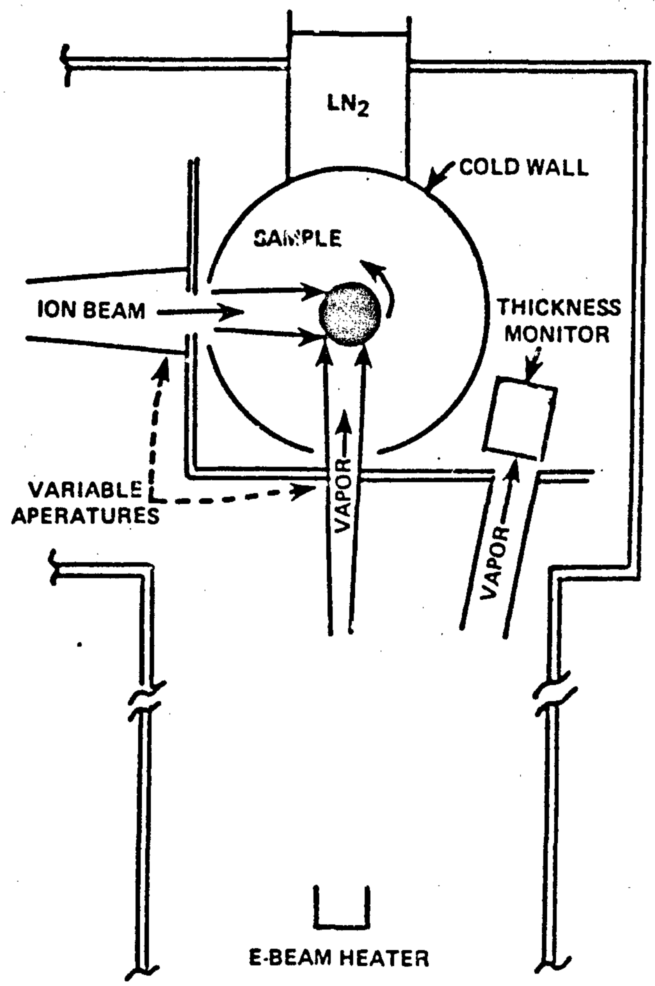
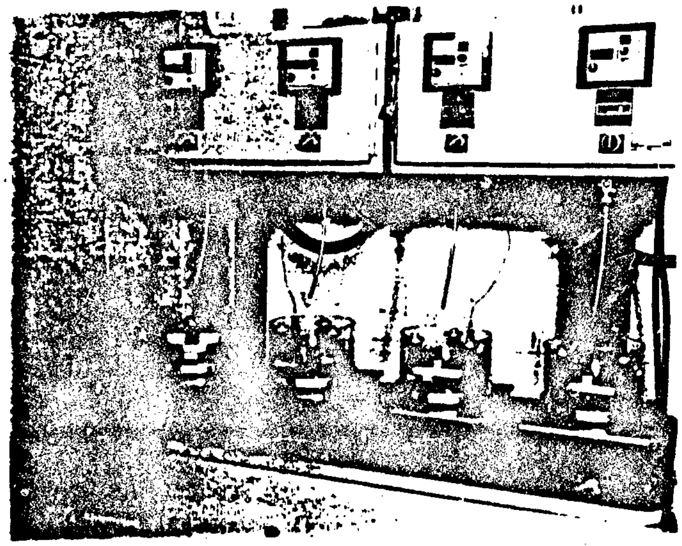


FIGURE 1 Schematic diagram of the Ion Beam Assisted Deposition (IBAD) System.



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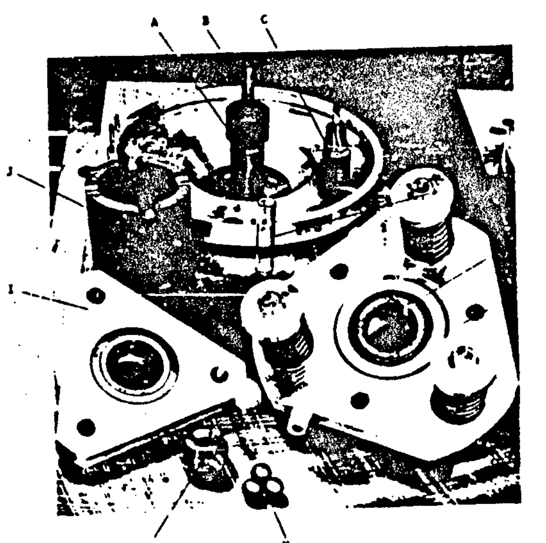
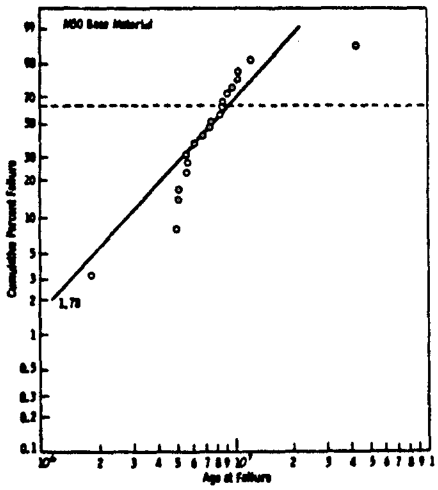


A. Collet/Nut
B. Test Bar
C. Accelerometer Pick-up
D. Plastic Guide
E. Lower Cup Housing
F. Middle Plate
G. Retainer
H. Three 1/2" Balls
I. Upper Cup Housing
J. Spacer

(b)

FIGURE 2 Rolling Contact Fatigue Rig:
(a) General View
(b) Ball/Rod Tester Components



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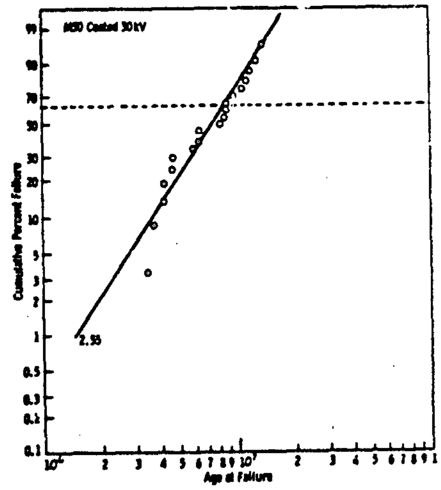

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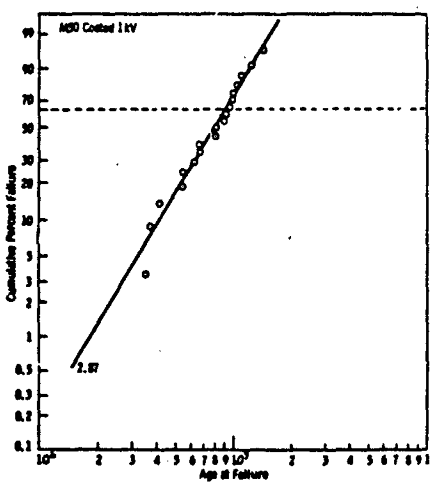

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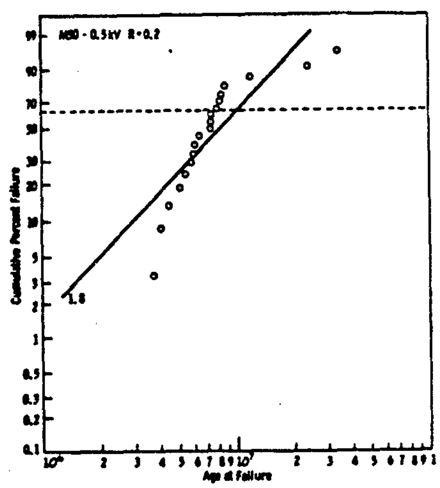

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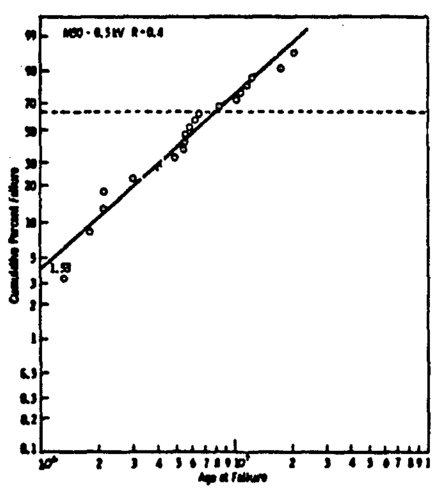


(e)

FIGURE 3 Weibull Distributions of M50 Base and 0.25μm TiN Coated, as a function of Cumulative Percent Failure vs. Number of Stress Cycles to Failure:
(a) M50 Base Material
(b) M50 TiN Coated at 30 keV
(c) M50 TiN Coated at 1 keV
(d) M50 TiN Coated at 0.5 keV, R=0.2
(e) M50 TiN Coated at 0.5 keV, R=0.4

Table 3

Process Condition for TiN IBAD Coatings

Sample	keV	Ion to Atom Arrival Ratio	Coating Thickness
SR1	0.2	0.3	1 mm
SR2	0.5	0.3	1 mm
SR1	0.5	0.5	1 mm
SR2	0.5	0.5	1 mm

Table 4

Stress Cycles to Failure for 1.0 μm coatings

Condition	B10	B50
Uncoated	5,664,424	10,770,445
SR2, 0.5 keV, R=0.5	8,017,377	40,114,720

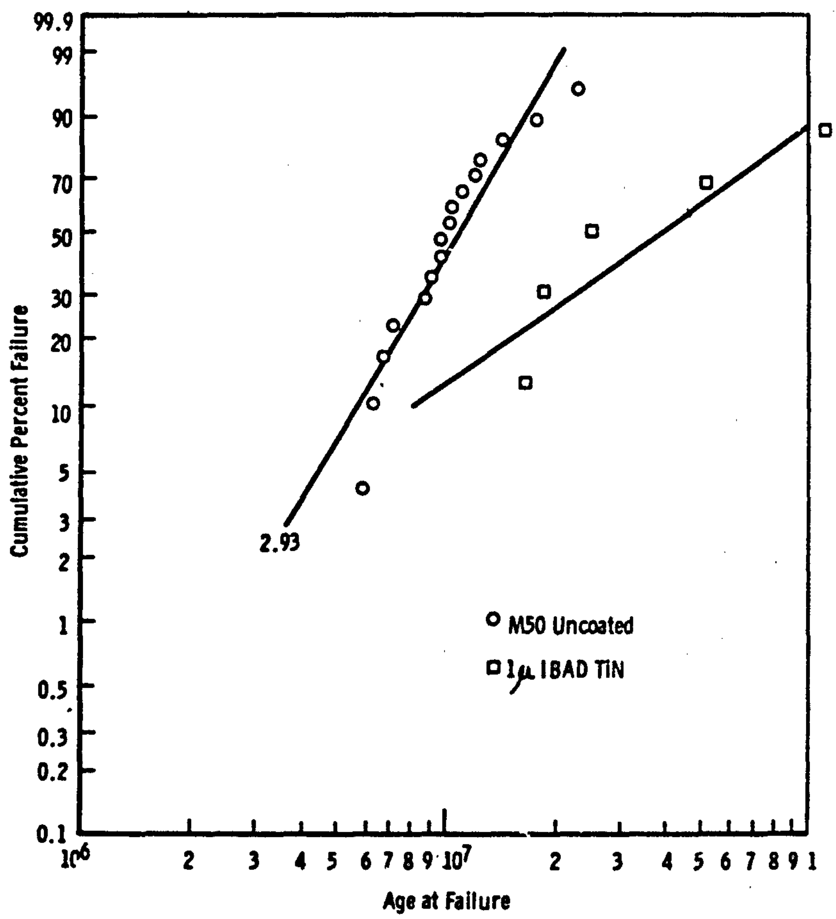
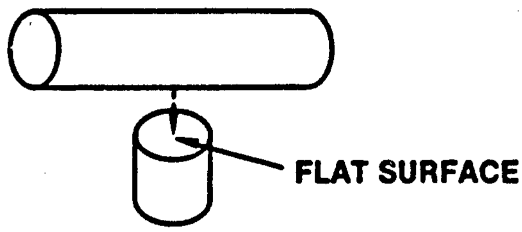


FIGURE 4 Weibull Distribution of M50 Base and 1.0 μm TiN Coated, as a function of Cumulative Percent Failure vs. Number of Stress Cycles to Failure.

1. Test pieces (identical alloy steel) were placed in contact as indicated by the dotted line.



2. Both pieces in place were immersed in chloride-contaminated oil for 2 hrs., removed, and allowed to dry.

3. A meniscus of contaminated oil was retained between the two parts:

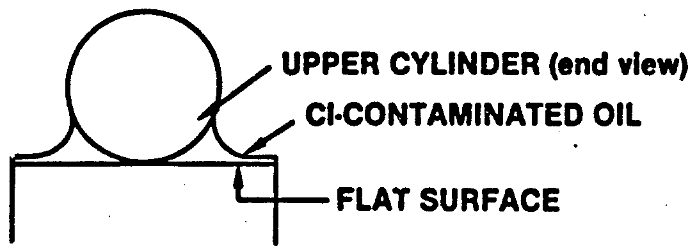


Figure 5. Schematic description of geometry used in corrosion test which simulates bearing field service conditions. Courtesy of F.A. Smidt, NRL

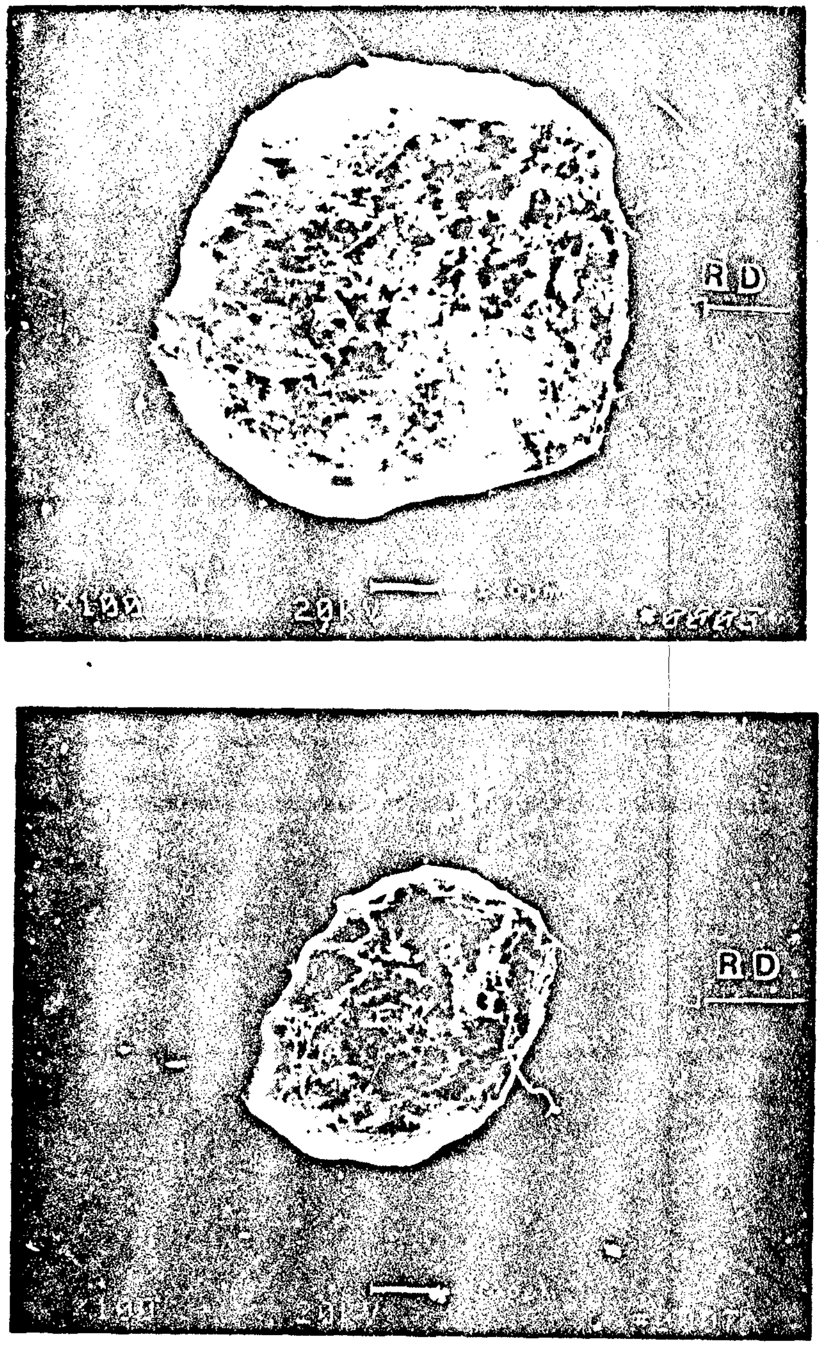
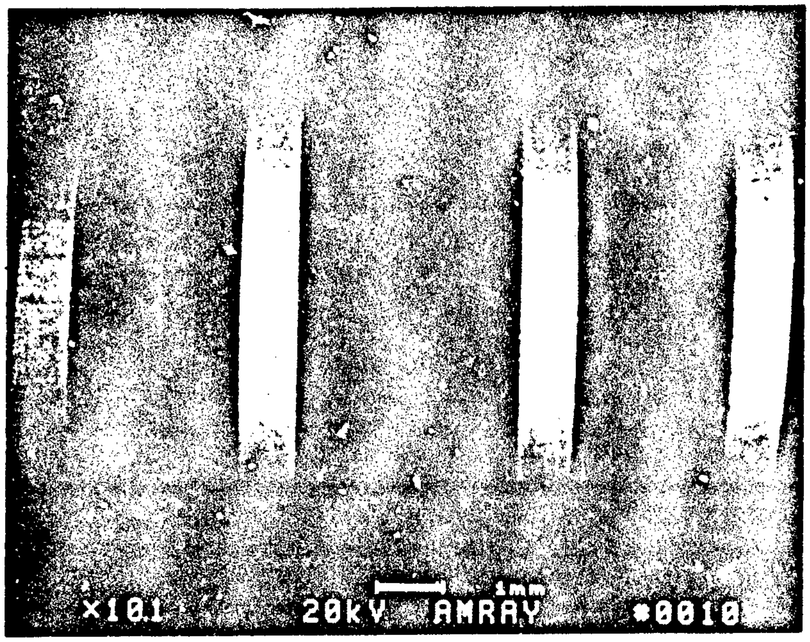


Figure 6. Typical Fatigue Spalls obtained in Rolling Contact Fatigue Testing.



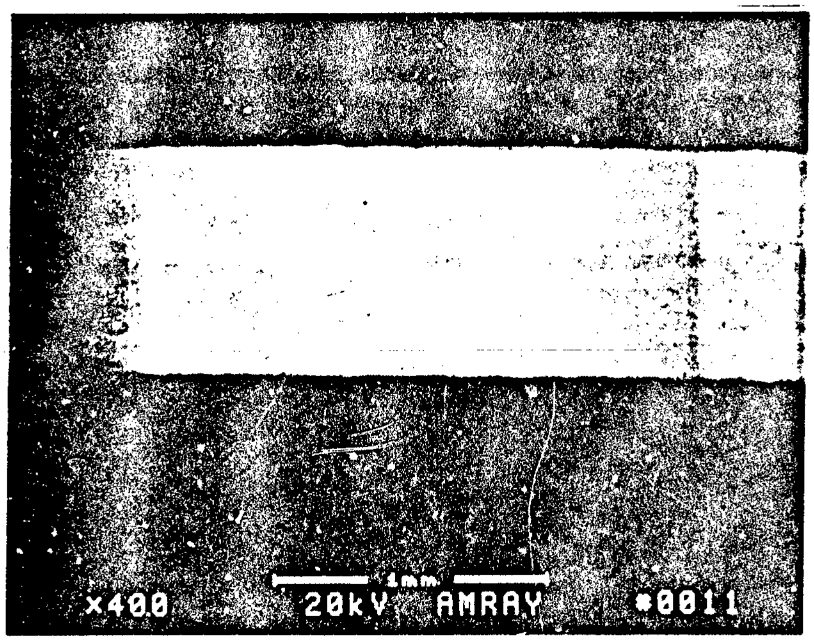
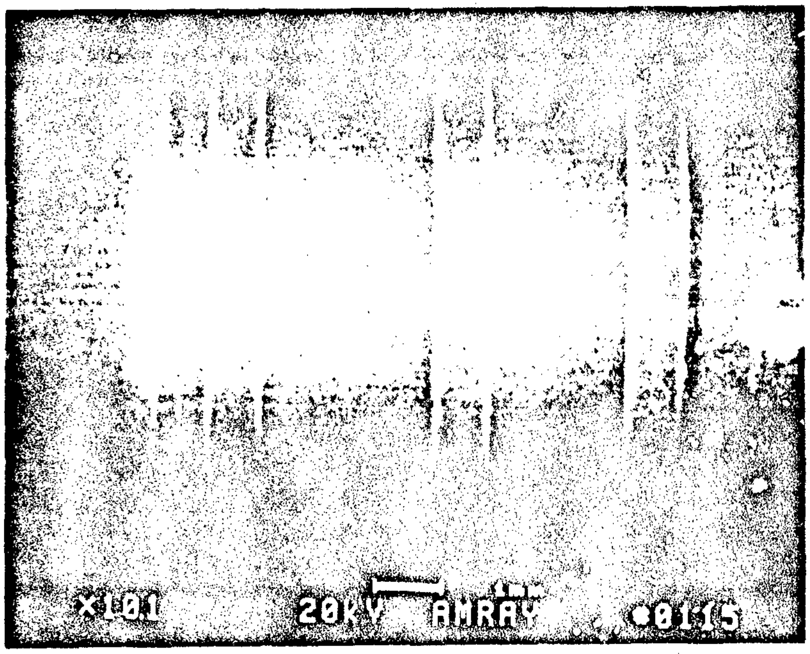


Figure 7. SEM micrograph (Backscatter Mode) of Wear Tracks. Specimen C2, 1 keV, R=0.03.



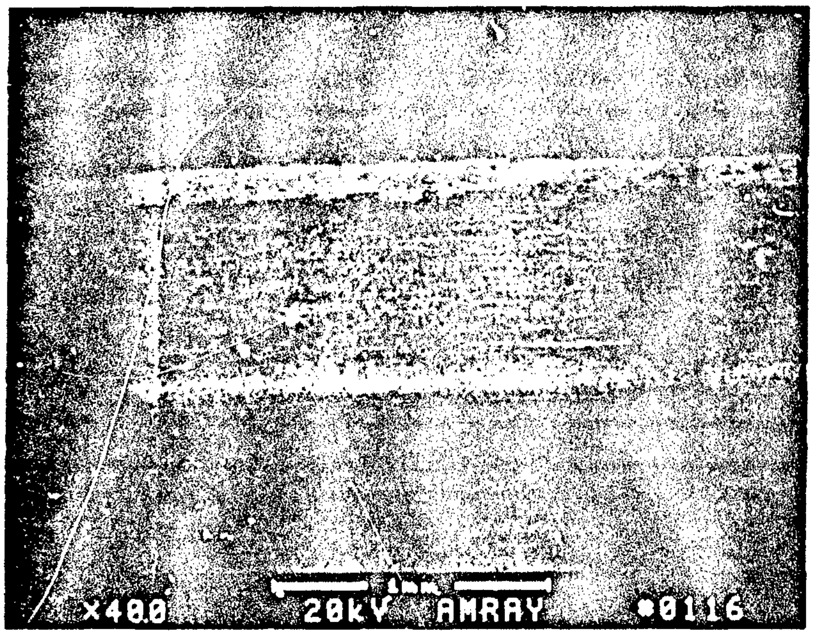


Figure 8. SEM micrograph (Backscatter Mode) of Wear Tracks. Specimen C2, 0.5 keV, R=0.2.

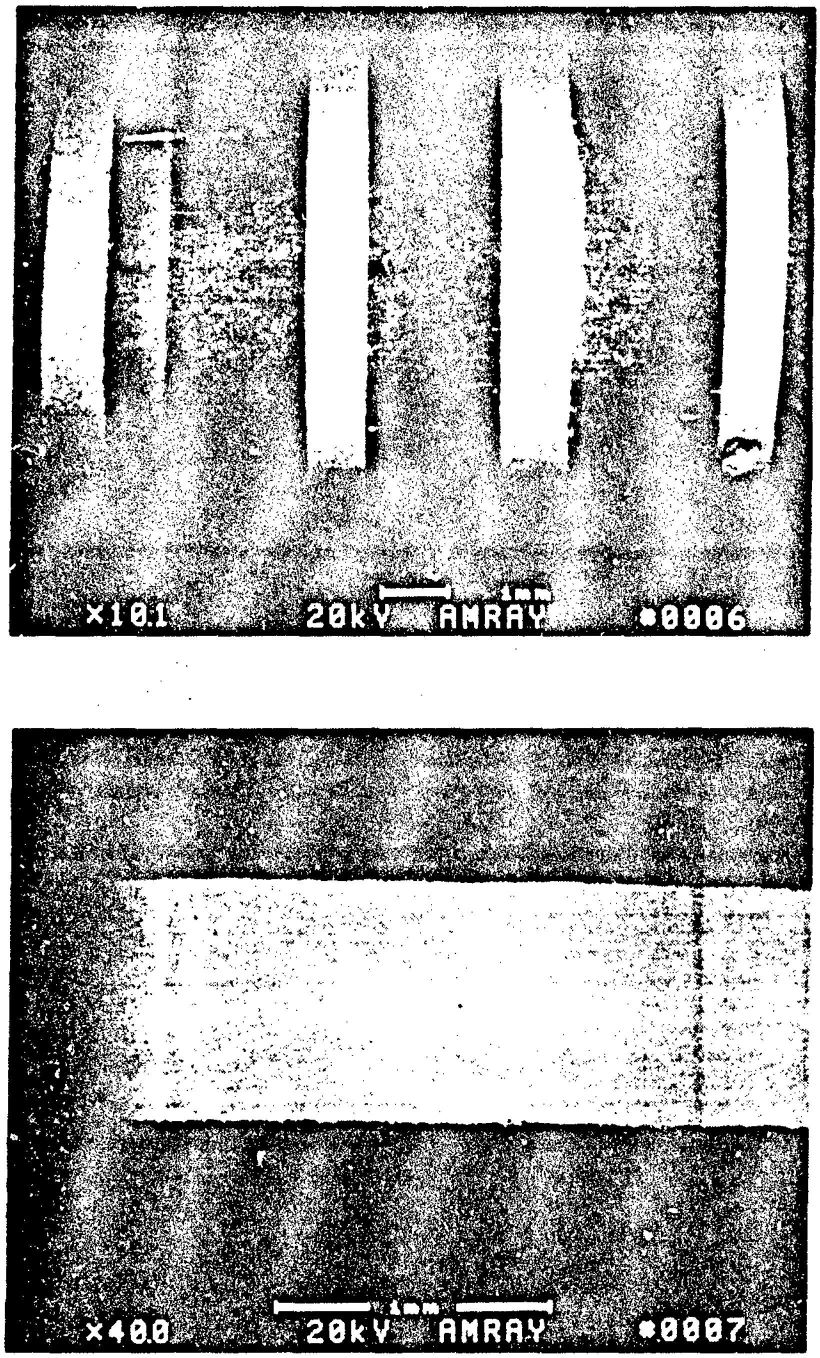


Figure 9. SEM micrograph (Backscatter Mode) of Wear Tracks. Specimen C9, 30 keV, R=0.03.

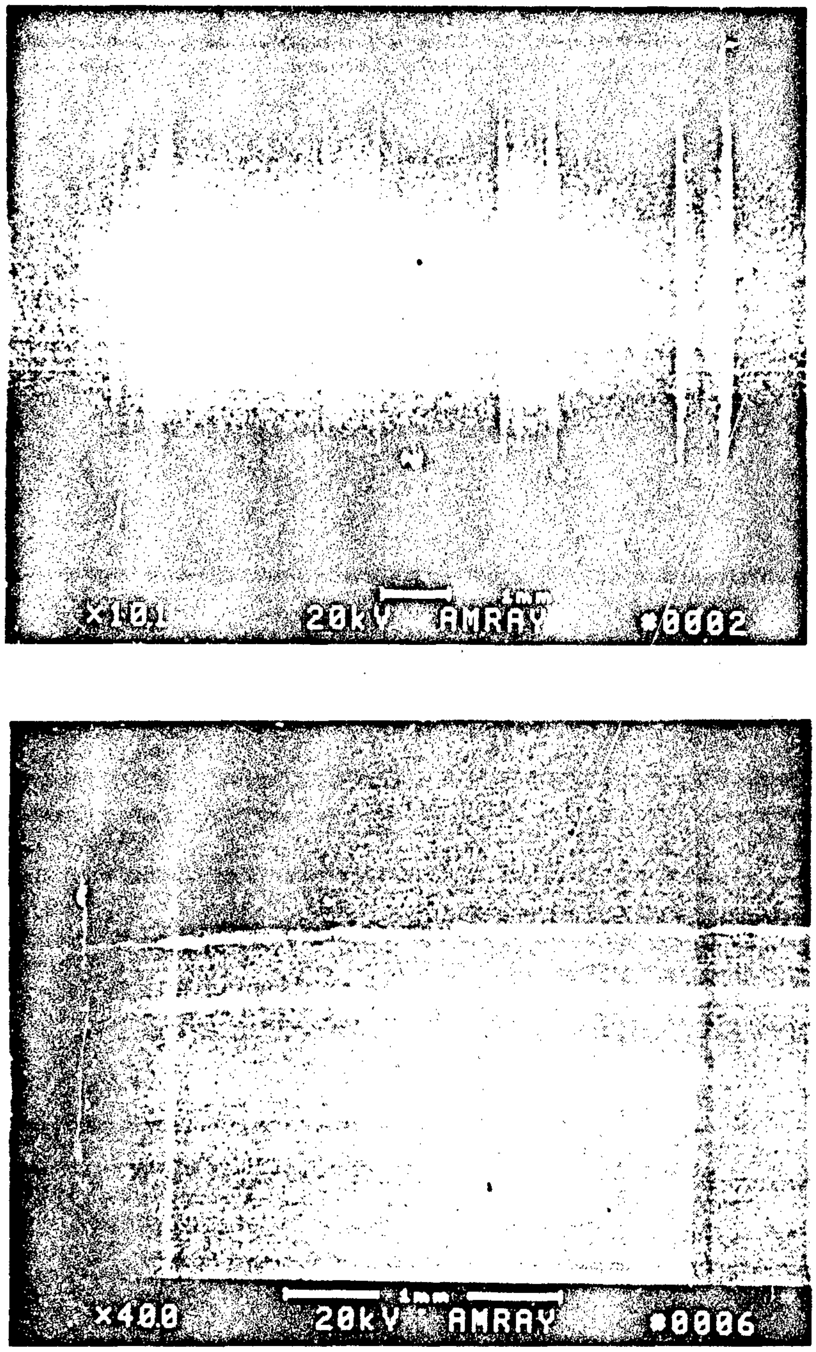


Figure 10. SEM micrograph (Backscatter Mode) of Wear Tracks, Specimen C9, 0.5 keV, R=0.4.

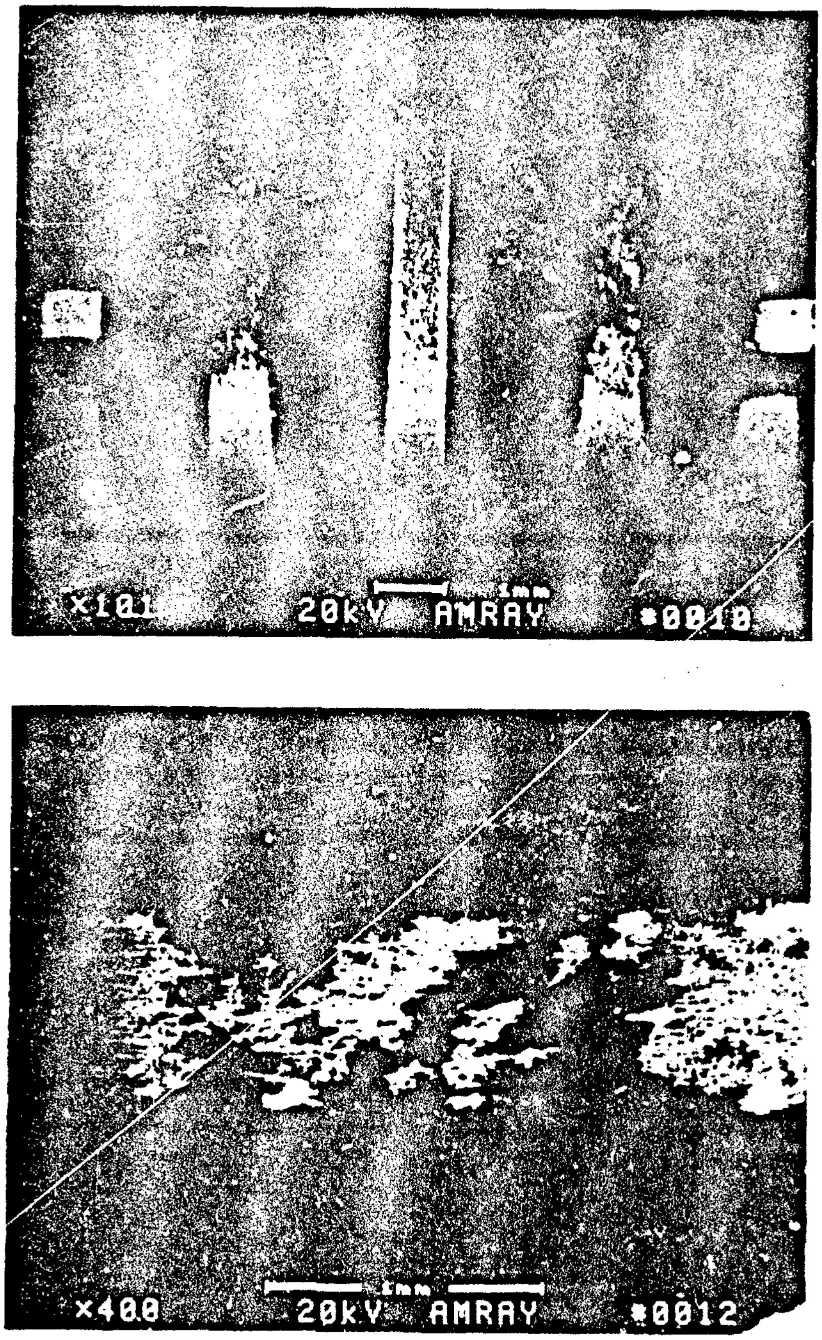


Figure 11. SEM micrograph (Backscatter Mode) of Wear Tracks, Specimen SR1, 0.2 keV, R=0.3.

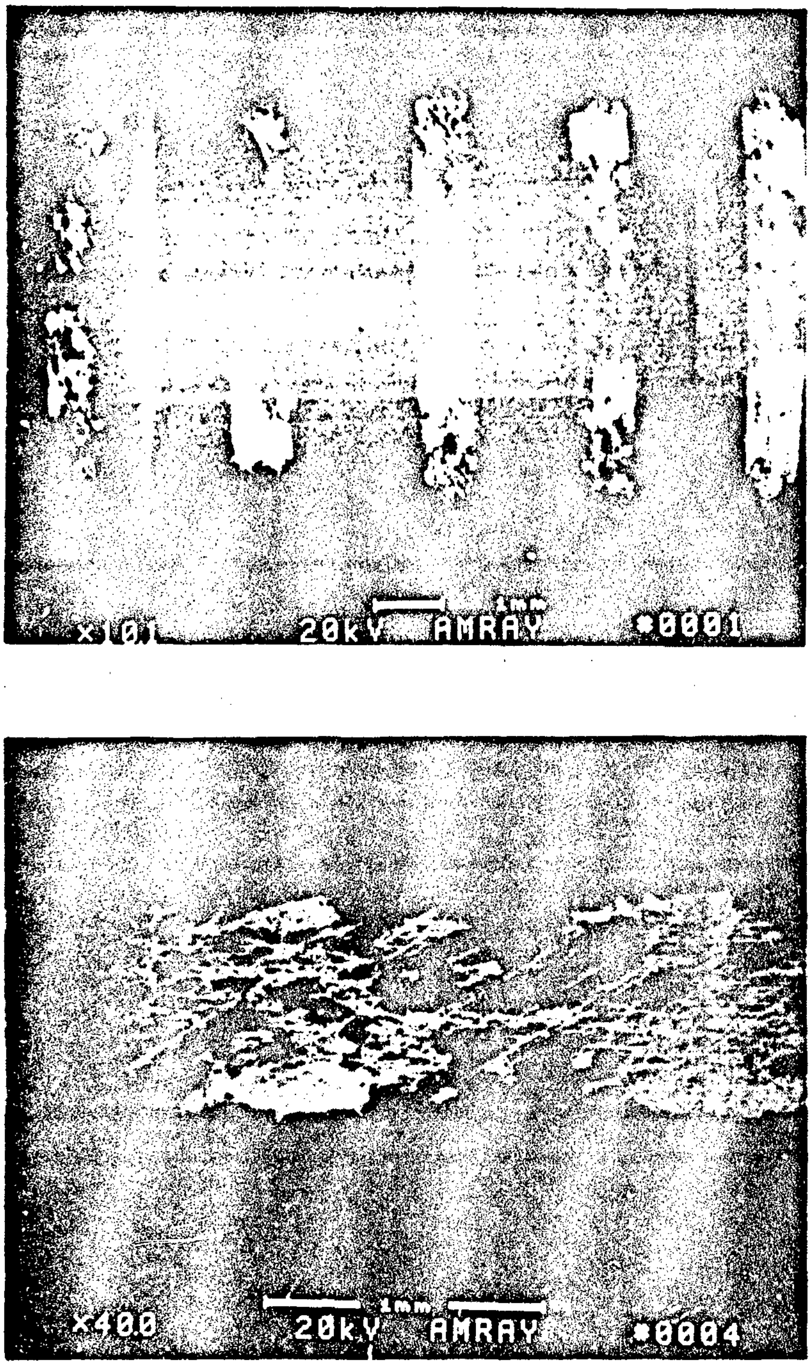
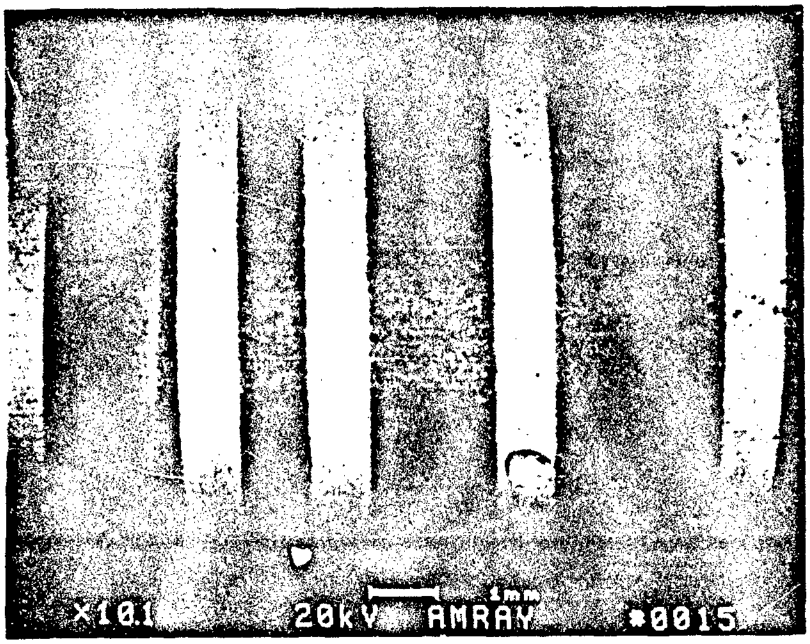


Figure 12. SEM micrograph (Backscatter Mode) of Wear Tracks. Specimen SR1, 0.5 keV, R=0.5.



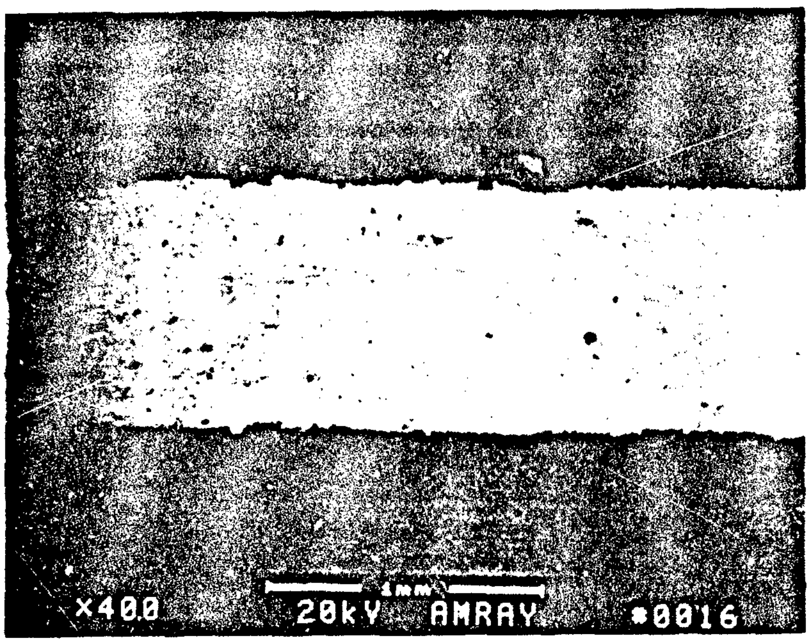
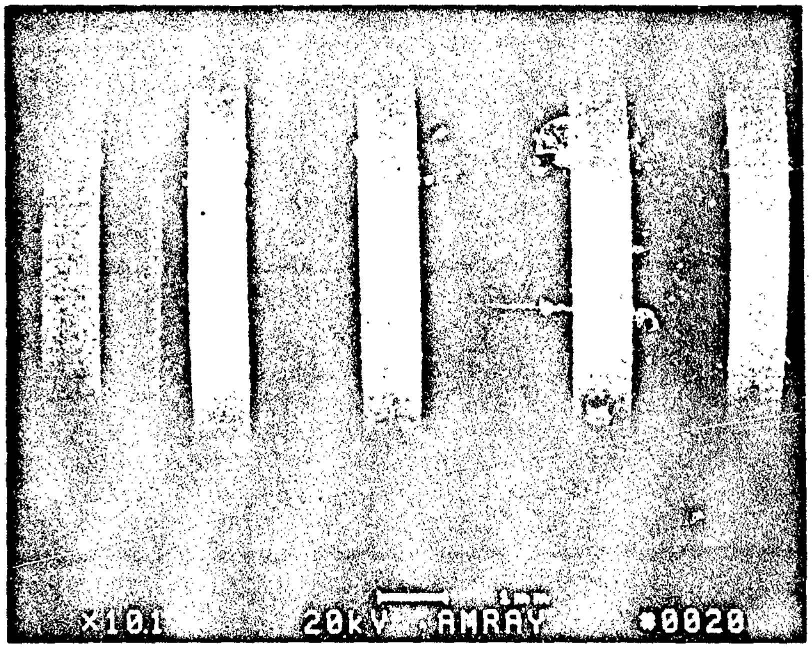


Figure 13. SEM micrograph (Backscatter Mode) of Wear Tracks, Specimen SR2, 0.5 keV, R=0.5.



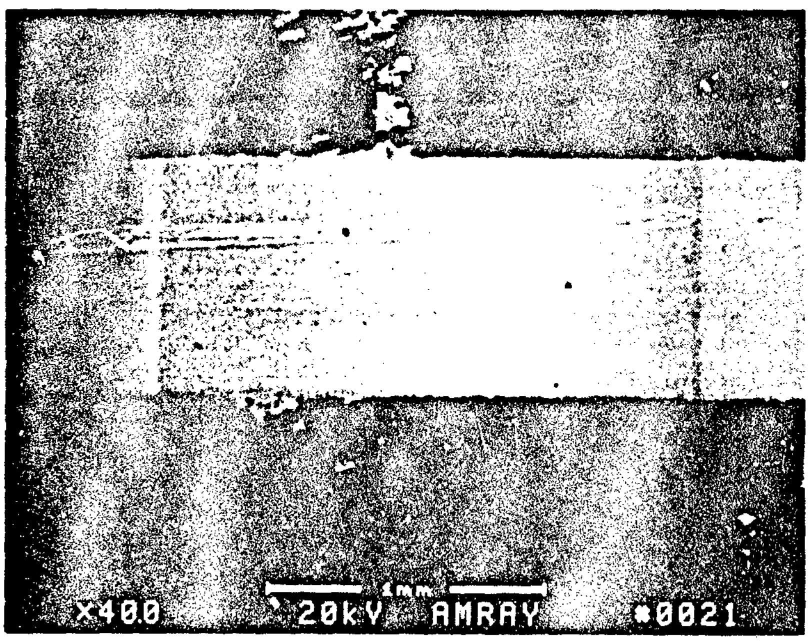
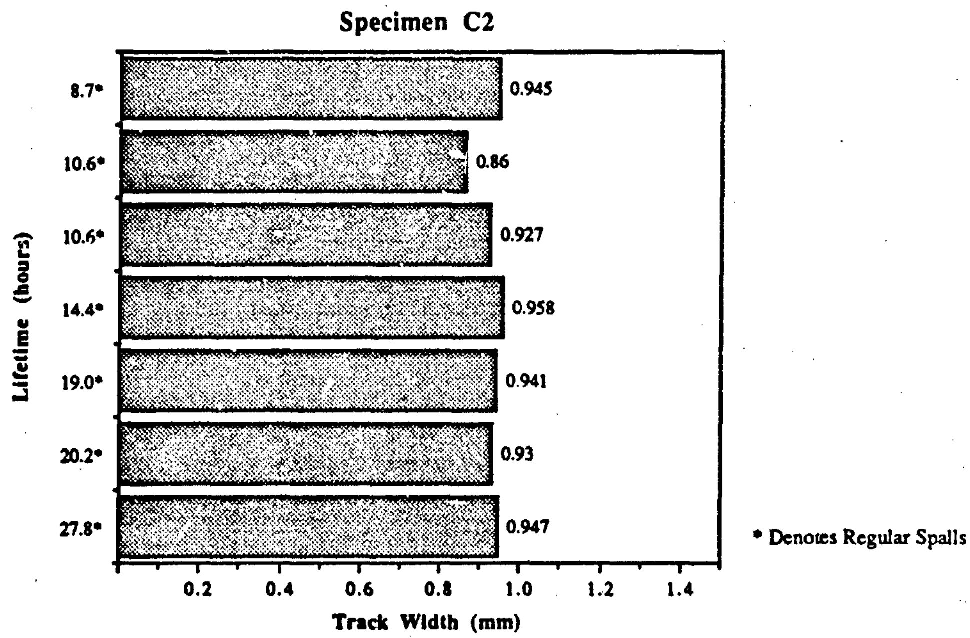


Figure 14. SEM micrograph (Backscatter Mode) of Wear Tracks, Specimen SR2, 0.5 keV, R=0.3.



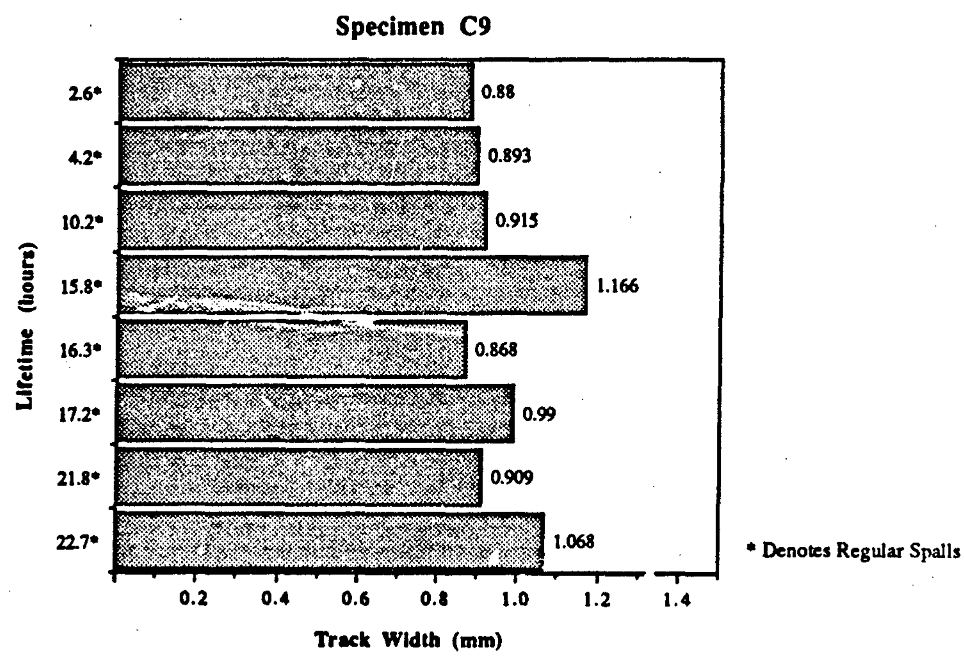


Figure 15. Track width measurements versus time to failure for randomly selected, 0.25 μm thickness coated RCF rods.

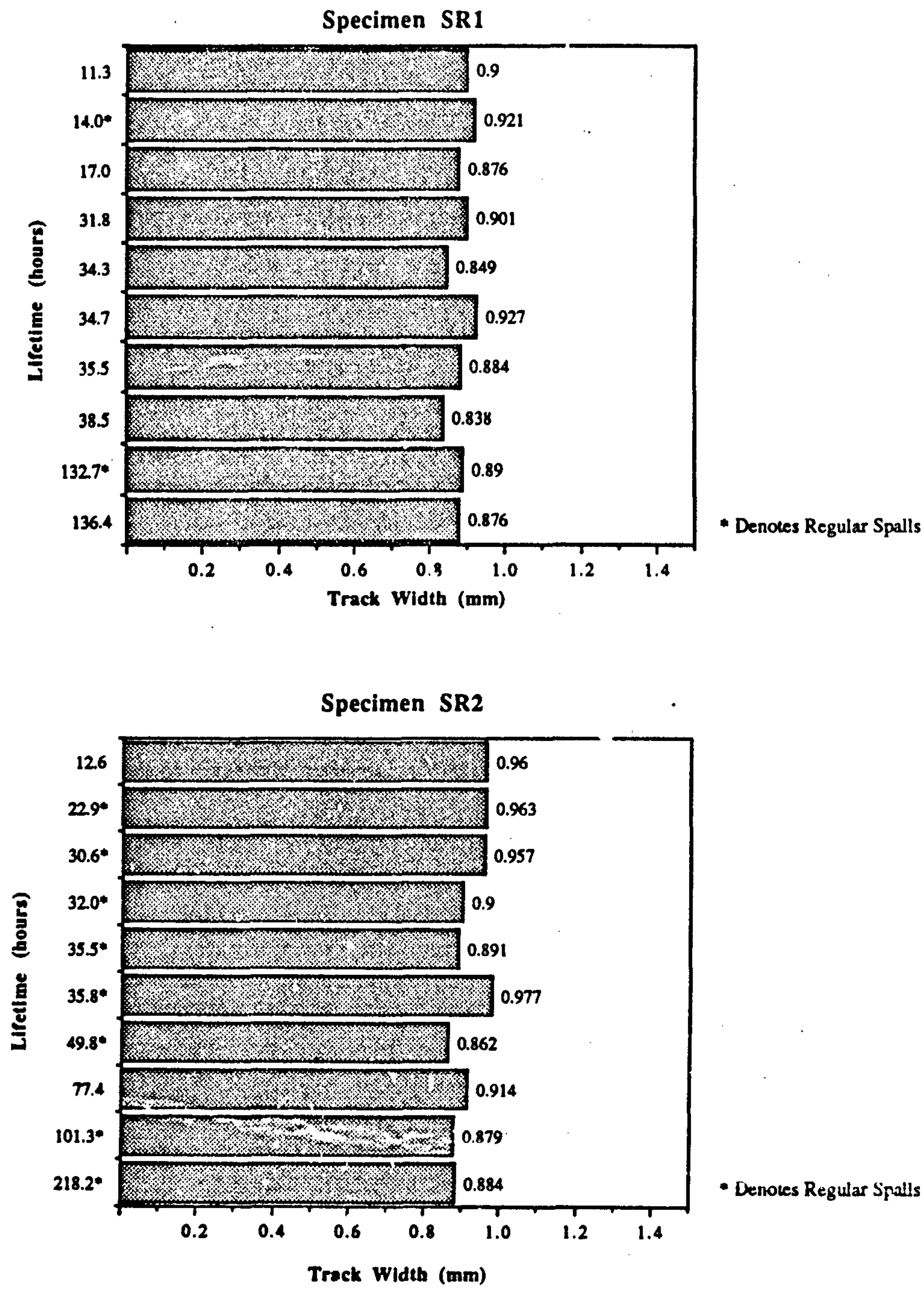


Figure 16. Track width measurements versus time to failure for randomly selected, 1.0 μm thickness coated RCF rods.

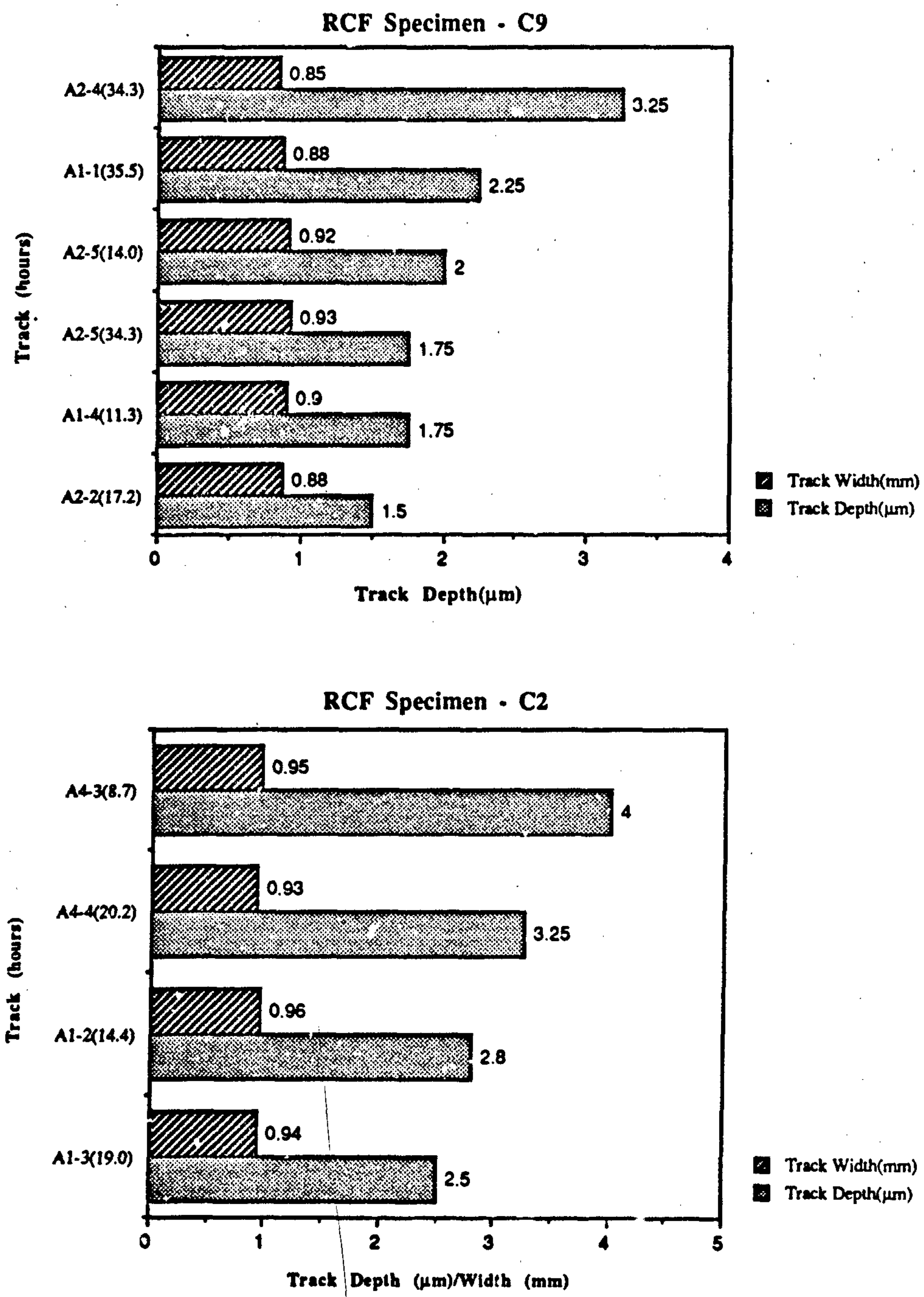


Figure 17. Comparison of track depth and width to hours to failure for selected wear tracks of 0.25 μm coating. Data from Table 5.

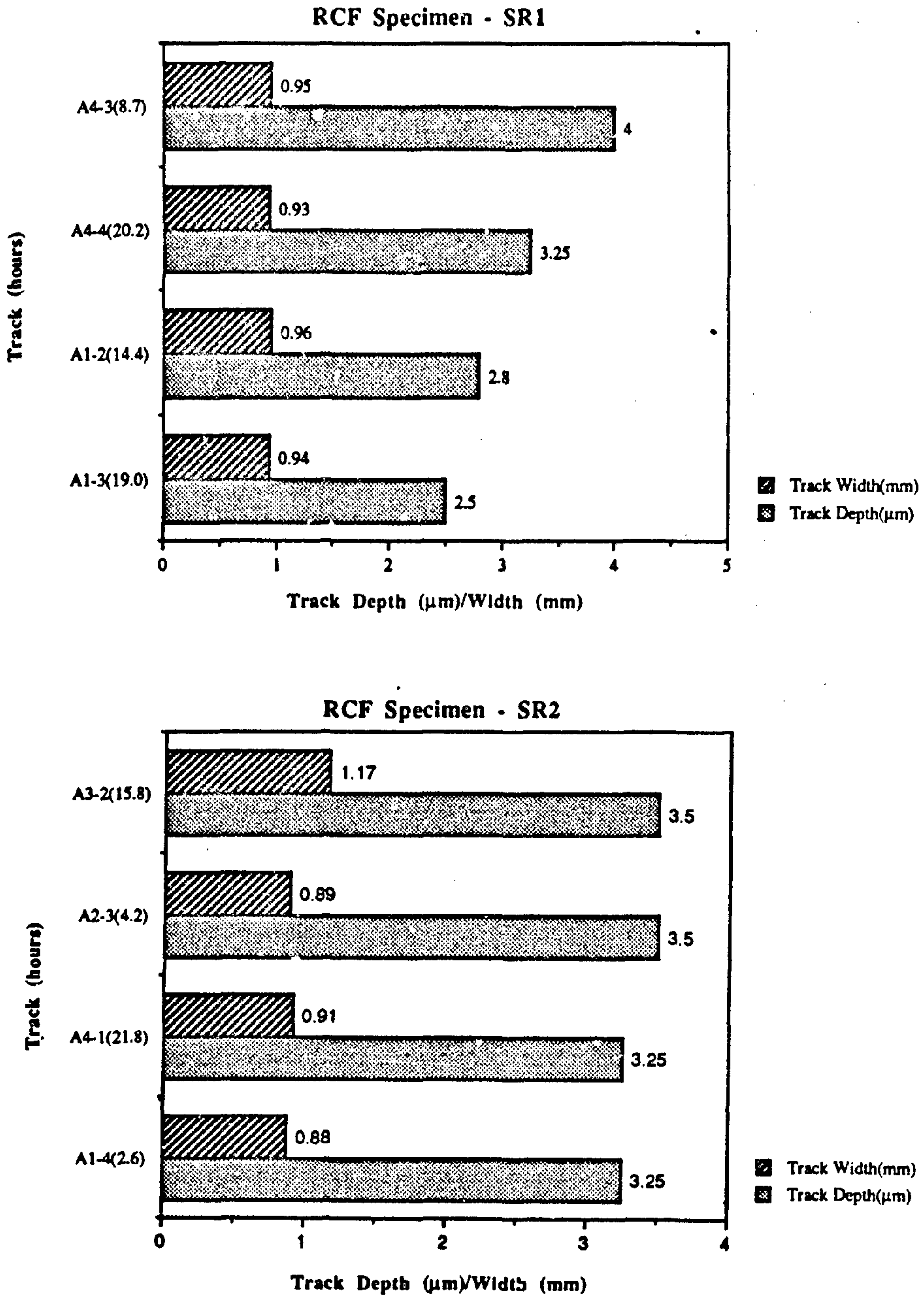


Figure 18. Comparison of track depth and width to hours to failure for selected wear tracks of 1.0 µm coating. Data from Table 5.

TABLE 5

<u>RCF Testing Of TiN IBAD</u>

Processing Parameters KeV	R	Track #	Specimen #	Machine #	Hours Run	Spall Type *	Track Width(mm)	Track Depth(μm)
0.50	0.20	1	C2	A2	10.6	RS	0.927	
0.50	0.20	2	C2	A1	14.4	RS	0.958	2.80
0.50	0.20	3	C2	A4	8.7	RS	0.945	4.00
1.00	0.03	1	C2	A3	27.8	RS	0.947	
1.00	0.03	2	C2	A2	10.6	RS	0.860	
1.00	0.03	3	C2	A1	19.0	RS	0.941	2.50
1.00	0.03	4	C2	A4	20.2	RS	0.930	3.25
0.40	0.50	1	C9	A4	16.3	RS	0.868	
0.40	0.50	2	C9	A3	10.2	RS	0.915	
0.40	0.50	3	C9	A2	4.2	RS	0.893	3.50
0.40	0.50	4	C9	A1	2.6	RS	0.880	3.25
30.0	0.03	1	C9	A4	21.8	RS	0.909	3.25
30.0	0.03	2	C9	A3	15.8	RS	1.166	3.50
30.0	0.03	3	C9	A4	17.2	RS	0.990	
30.0	0.03	4	C9	A4	22.7	BS	1.068	
0.50	0.50	1	SR1	A1	35.5	BS	0.884	2.25
0.50	0.50	2	SR1	A2	17.0	BS	0.876	1.50
0.50	0.50	3	SR1	A2	31.8	BS	0.901	
0.50	0.50	4	SR1	A1	11.3	BS	0.900	1.75
0.50	0.50	5	SR1	A2	14.0	RS	0.921	2.00
0.20	0.30	1	SR1	A2	38.5	BS	0.838	
0.20	0.30	2	SR1	A2	136.4	BS	0.876	
0.20	0.30	3	SR1	A1	132.7	RS	0.890	
0.20	0.30	4	SR1	A2	34.3	BS	0.849	3.25
0.20	0.30	5	SR1	A2	34.3	BS	0.927	1.75
0.50	0.50	1	SR2	A2	22.9	RS	0.963	
0.50	0.50	2	SR2	A1	35.8	RS	0.977	
0.50	0.50	3	SR2	A1	12.6	BS	0.960	
0.50	0.50	4	SR2	A2	30.6	RS	0.957	3.00
0.50	0.50	5	SR2	A1	77.4	BS	0.914	2.75
0.50	0.30	1	SR2	A1	218.2	RS	0.884	2.50
0.50	0.30	2	SR2	A2	101.3	RS	0.879	2.50
0.50	0.30	3	SR2	A1	35.5	RS	0.891	
0.50	0.30	4	SR2	A1	49.8	RS	0.862	
0.50	0.30	5	SR2	A2	32.0	RS	0.900	

* RS - Regular Spall
BS - Ball Spall

APPENDIX A

Comments on Goals and Objectives

In 1980 the Corpus Christi Army Depot, housing the largest bearing shop within the Army, was processing 200,000 bearings annually with 400 different part numbers and with a replacement value of $10 million. The individual bearings ranged in price from $1.00 to $2,073.00. Supply, storage, management, and economic studies[18] indicated that a refurbishment of the most widely replaced bearings with a replacement value of more than $ 80 each could result in a 45 % savings for those bearings. Accordingly, CCAD embarked on an aggressive refurbishment program to achieve these savings. Even so, in 30% of bearing inspection during overhaul, the used bearings were scrapped, and the replacement value of these was over $3 million in 1980 dollars. Assuming a doubling of cost estimates to bring these figures up-to-date, then the potential for significant savings by increasing the useful lifetime of operating bearings is staggering. Increasing lifetime performance of bearings through various coating procedures is one of the main goals of the MTL gear and bearing program.

Specifications for the various components, engine, transmission, accessory gearboxes, rotor head, etc., dictate the time-before-overhaul [TBO] for these elements. During overhaul classification of used bearings for rework and potential reuse requires bearings to be subjected to 100% inspection, both diagnostic and dimensional. The largest number of bearing rejects in engines and transmissions is due to dimensional discrepancies and pitting corrosion. That is, the bearings are rejected before having reached their material endurance lifetime. Why then focus on improved lifetime performance rather than simply concentrating on the phenomena prompting bearing rejection? As pointed out recently at an Operation and Support Cost Reduction [OSCR] briefing, by one of the authors of this report, the attempt to contain maintenance costs for the Army's large inventory of vehicles is not a static situation. Therefore, concentration on only materials and components of *presently fielded systems* is a short-term approach which will furnish negative results in long-term savings to investment. One must understand that support of the Army inventory is a three pronged effort, involving economic analysis [OSCR], new design and developments [upgrade], and combat mission requirements [readiness]. How each of these factors affect the cost of doing business is relatively apparent. For example, concentrating only on pitting or corrosion of present operational systems does not factor in increased requirements of emerging systems with faster speeds, higher temperatures and higher loads, which demand enhanced lifetime performance. Moreover, component upgrades developed susequent to system development, increase costs by requiring maintenance of additional bearing inventory. Combat mission requirements that stipulate readiness availability in order to interdict potential threats, add substantially to bearing replacement costs through the escalated price for odd-lot acquisitions and short deadline delivery. Only with a comprehensive project directed toward all these concerns, will actual long term savings to investment costs be realized. This will come with rapid insertion into the vehicle system of increased endurance, corrosion resistant, coated bearings which now show great promise in the laboratory. The intent is to comparatively rate the coating and substrate combinations through simulation testing and characterization and then down-select to the most promising combination[19]. Engineering followup through field and component testing is intended to foster speedy insertion in vehicle systems, thereby shortening laboratory-development to field-utilization lead time.

The benefits derived from such an approach are numerous. First, is the continued use of a large percentage of bearings presently rejected during overhaul due to pitting or corrosion. The enhanced corrosion and spalling retardation resistance of coatings will allow this. Second, is a reduction in the costs associated with refurbishment of used bearings, albeit that this represents 55% of the cost of new bearing replacement. Table A1 shows the operations involved in bearing refurbishment. The first three steps are a constant and cannot be changed with 100% inspection. However, if the bearing can be returned to service without initiating some or all of the following 12 steps, then a considerable cost savings is realized. The enhanced bearings will permit this for a much larger percentage of cases. The third benefit comes with operational experience of the improved bearings. When experience indicates that these bearings can be reused without refurbishment, then the time between overhauls can be extended, contributing to cost savings as well as increased readiness of the combat system. Fourth, is the development and certification of improved performance bearings, prior to and during, the development of advanced systems that will utilize them. This chronology allows insertion at system completion, rather than subsequent design, testing and certification of bearings to meet the new specifications and requirements of the advanced vehicle system following system completion.

To achieve the stated goals this program has investigated several coatings and coating processes and is presently involved with studies of additional coatings and different substrates. Results with ion plated ZrN, electroplated thin dense chromium [TDC], and IBAD TiN, all with a 1 µm nominal thickness, coated on M50 steel, have shown considerable lifetime improvement. Ion plated Cr and ion plated Cr deposited over ion plated ZrN on M50 do not display a statistically significant improvement. In addition, testing is being conducted on diamond-like carbon [DLC] coatings and catalytic surface conversion processing of M50 steel. Studies of powder metallurgy alloys, carburizing grade substrates such as M50 NiL and a stainless carburizing grade EX 98 [present nomenclature, Pyrowear 675] are underway. Finally, a collaborative effort with the Ceramics Research Branch to study foreign and domestic Si_3N_4 rolling elements for utilization in hybrid bearings is in progress. Reports will be issued upon completion of characterization and testing in each of these studies.

TABLE A1

Bearing Refurbishment Operations

1. Bearing disassembly
2. Visual inspection
3. Dimensional inspection
4. Stripping silver plate from cages to facilitate inspection
5. Honing of raceways
6. Replacement of rolling elements
7. Replacement of inner races if used races are damaged beyond capability of honing to repair
8. Replacement of cages, if necessary
9. Magnetic particle and nital etch inspection of new inner races
10. Fluorescent penetrant inspection of cages, new and used
11. Silver plating of cages
12. Balancing of cages
13. Correcting face flushness or duplex on ball bearings
14. Reassembly of bearings, bend lugs or rivet as required
15. Reinspecting, preserving, packaging, and shipment

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